GBT Memo No. 58

To : GBT Memo Series

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Subj : Beam-switching on the GBT

Introduction

At frequencies above 5 GHz, both broad-band spectroscopy and continuum measurements can benefit greatly from some form of beam-switching. Beam-switching is any technique which allows one to take the difference of signals received from two (or more) positions in the sky, without having to physically move the telescope. For broad-band spectroscopy, this tends to provide better baselines than either position or frequency switching, while for continuum observations a large percentage of the rapid fluctuations caused by atmospheric emission are eliminated. Without beam-switching, the capabilities of the GBT above 5 GHz would be severely curtailed.

To date, beam-switching has been achieved either

1) through multi-feed receiver systems, both with or without waveguide switches,

2) by nutating or wobbling some component in the telescope optics, often the subreflector, or,

3) via a quasi-optical chopper.

In this report, we present our thoughts on the advantages and disadvantages of the different methods of beam-switching, concentrating on possible implementations for the Green Bank Telescope (GBT), and implications for the science to be performed with the instrument. To this end, we divide the various methods of beam-switching under four separate class headings. Our conclusions are summarized in the Appendix at the end of the report.

Multi-feeds with Waveguide Switches

This is the case where the receiver is cycled between multiple feeds using a waveguide switch to perform the switching. It includes both the simple Dicke system and Double-Dicke system. In the Double-Dicke configuration, a pair of feed horns are switched in antiphase between two separate receiver chains. The presence of the switch between the feed and receiver will inevitably degrade the receiver performance (i.e. raise the effective system temperature). The loss in the switch depends on frequency, and can be quite low at the lower frequencies , especially if the switch is cryogenically cooled. In contrast, waveguide switches are not currently available in the millimetre-wave region. Dicke-switched receivers tend to be costlier than simple total-power receivers, especially Double-Dicke systems where two receiver chains are required. In recompense for the degradation of performance, switching rates with these receivers can be considerably more rapid (> 100 Hz) than with nutating devices. This can result in greater supression of atmospheric emission and 1/f noise. Further, Dicke switching has lower switching overheads than nutation, meaning less blanking time, and increased effective observing time.

Unlike nutators, multi-feed receivers are relatively inflexible should it be desired to change the separation and orientation of the beam positions in the sky. The mechanical and electrical complications of any such change preclude its being a routine operation. Observations with three or more beam positions require the extra cost and complexity of additional feed horns and switches. However, with extra receiver chains, all beam positions can be observed for essentially 100 % of the time. As a simple example of this, the perfect Double-Dicke system gains root two in signal-to-noise over either the simple Dicke system or the simple nutating subreflector. We note that to obtain full spatial-frequency coverage of the sky, observations from two non-commensurate beam separations are required.

Multi-feeds without Waveguide Switches

Here, a multi-feed system is used without any moving parts before the receiver. There are two essentially-different variants, the correlation receiver and software beam-switching (SBS). The correlation receiver eliminates any need for blanking and has the same root two sensitivity gain as the Double-Dicke receiver. However, the presence of a hybrid-ring represents a lossy component in front of the receiver. As with the Double-Dicke system, at least two receiver chains are needed. A quasi-optical hybrid-ring has been used on a correlation receiver at 97 GHz.

The SBS technique (Morsi and Reich, Astr. Astrophys., 163, 313) uses separate high-stability total-power receivers, which are recorded directly by the acquisition computer, then calibrated and subtracted off-line to give the beam-switched signal. The technique has been used up to 32 GHz and was especially developed for use with arrayed receivers. If N receiver chains are available, N(N-1)/2 independent beam-switched channels are available. This method dispenses with any extra lossy components in the signal path, and signal and reference positions are again observed continuously, resulting in a root two sensitivity gain. For spectral line observing, the differing passbands of different receivers would appear to present a complication.

The Nutating Subreflector

By nutating the secondary reflector, a simple total-power system can be used to beam-switch with no pre-feed losses. The high inertia of the secondary in the case of the GBT may limit switching rates to about 1 Hz. We would also expect a significant loss of observing time in the overhead needed to move the subreflector between positions. With rapid switching, the subreflector may deform in shape, producing a slight reduction in the aperture efficiency. The problem of how well the torques associated with nutation can be compensated will need to be investigated.

With a nutator, the user can easily change the separation and orientation of the beam positions in the sky, including (at a cost) tracking parallactic angle. One could also build a nutator which allows a number of 'off' positions to be observed for each 'on'. While a sophisticated backend would then be needed to accumulate the data from each position, the same is desirable for all the systems described here. Mismatches between the signal paths arise only in the optics and should be less than for the above beam-switching methods.

Perhaps the greatest disadvantage of a nutating secondary is the initial cost of the mechanism. However, it is to be noted that subreflector movement will be needed not only for nutation, but to correct pointing errors which are too rapid to be eliminated by telescope movements. The incremental costs of a nutation mechanism is the relevant quantity.

Nutating Tertiaries, Quasi-optical Choppers, etc.

Nutation of a tertiary mirror, or other component in the optical path to the receiver, has many of the advantages and disadvantages of nutating the subreflector. However, the smaller inertia of a tertiary reflector means that it can be nutated at a higher rate, with possibly less overhead in movement. It should also be cheaper to build and easier to maintain, while deformations during nutation should not be a problem. Given the positioning of the secondary focus on the GBT, a study would be needed to examine the practicality of a nutating tertiary which could also be used to correct for irregularities in the pointing.

Rotating quasi-optical choppers have been used extensively at millimetre wavelengths, both at and away from the focal plane. At radio wavelengths their sizes could be prohibitive. As with tertiary reflectors, an extra reflection with its associated loss is introduced before the receiver.

Conclusions

The trade offs between the above systems need to be considered and an early decision made. All the systems have drawbacks and we must ask which we are prepared to live with. To chose against subreflector nutation now may mean that the final GBT design will not allow its addition in the future. In economic terms, nutation of any optical elements is a one-time-only expense, while multi-feed beam-switching implies greater cost for future receivers, although there is an associated sensitivity gain with multiple-chain receivers. Scientifically, the gain with a multi-feed system due to rapid switching and little or no blanking must be balanced against receiver mismatches, higher system temperatures and inflexible beam separations. The lack of losses, minimal receiver mismatch and ease of changing beam separation with a nutating subreflector must be balanced against slow switching, high blanking overheads and possible mechanical complexities. Is a nutating tertiary a satisfactory compromise? Clearly the situation needs careful and informed consideration.

Appendix

Advantges and Disadvantages of Different Methods of Beam-switching

A) Multiple Feeds with Waveguide Switches

Advantages

1) Rapid Switching (~100 Hz) -- better weather and 1/f rejection.

2) Small transition time -- little blanking.

3) For Double Dicke, both signal and SAME reference observed continuously -- root two better signal-to-noise.

4) Easily extended to FEW beam Rxs -- several beam throws simultaneously.

5) No mechanical movement at prime focus.

6) Lessens basic cost of telescope.

Disadvantages

1) Switches not available in millimetre window.

2) Switches represent loss IN FRONT OF the preamp (cooled switches needed)

3) For Double Dicke, a second Rx chain needed.

4) Difficult to adjust beam throw.

5) Complex for arrayed receivers.

6) Receivers may be costlier.

B) Multiple Feeds with Correlation Rx or Software Beam Switching (SBS)

Advantages

1) No switching -- No blanking + best possible weather rejection (1/f Rx noise not intrinsically rejected?)

2) Same signal + reference observed continuously -- root two gain over simple Dicke or nutator.

3) For SBS, no lossy components between horn and Rx.

4) Correlation Rx easily extended to FEW beam Rx -- several beam throws simultaneous.

5) SBS is good for arrayed receivers, giving N(N-1)/2 separations.

6) No mechanical movement at prime focus.

7) Lessens basic cost of telescope.

Disadvantages

1) SBS needs very stable Rx's + cal.system. Has not been tried above 32 GHz.

2) Two Rx chains needed (or >2).

3) Difficult to adjust beam throw.

4) For Correlation Rx, the hybrid ring represents loss IN FRONT OF preamp. Hybrids are tricky at millimeter wavelengths (quasi optics?)

5) Correlation Rx complex for arrayed receivers.

6) Receivers may be costlier.

7) Not been tried for spectroscopy.

C) Nutating Subreflector

Advantages

1) No lossy compts. between horn + Rx.

2) Easily adjusted throw and orientation.

3) Works equally well to the highest frequencies.

4) Gives N separations for an arrayed Rx with identical throws for each element.

5) More than two selectable positions could be made available.

6) Receivers as simple as possible.

Disadvantages

1) Slow switching rate (< few Hz).

2) Long transition time -- much blanking.

3) Cannot observe signal and SAME reference all the time.

4) Cyclic torque at the prime focus.

5) Can only observe one beam throw at a time for two-position nutation.

6) Possible mechanical problems (Deformation with nutation).

7) Cost of nutation mechanism.

D) Tertiary Nutator, Chopper, etc.

Advantages

1) Probably better at high frequencies.

2) Can switch reasonably quickly (~ 10 Hz).

3) Easily adjusted beam throws.

4) Rocking tertiary could be used for arrayed receivers.

5) Multiple beam throws possible with rocking tertiary.

Disadvantages

1) Noticeable transition times.

2) Cannot observe signal and same reference all the time.

3) An extra reflection loss is introduced.

4) Focal Plane choppers are essentially single Rx devices.

5) Size increases with wavelength.